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Wild Salmonid Sea Lice Monitoring in the Icelandic Westfjords 2024

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LIST OF CONTENTS

ABSTRACT

The Icelandic and international salmon farming industry is currently grappling with significant challenges posed by high sea lice infestations, which adversely affect the welfare and health of both farmed and wild salmonids. This study investigated sea lice infestation levels on wild salmonids in the Icelandic Westfjords, focusing on the impact of temperature on lice abundance and the correlation between lice levels on wild and farmed fish. A total of 4,722 lice were recorded on 174 fish, with approximately 70% of the captured fish carrying sea lice. Among the preadult and adult lice, 98% were salmon lice (*Lepeophtheirus salmonis*), with only two identified as fish lice (*Caligus elongatus*).

The study revealed considerable variation in sea lice abundance across different months and sampling sites. Model results suggested that water temperature is a strong driver of sea lice abundance on wild salmonids, with higher temperatures correlating with increased infestation levels. The data further highlighted a strong correlation between lice loads on wild fish and the abundance of adult female salmon lice on nearby fish farms. Wild fish in areas with high lice densities on farms exhibited significantly higher infestations, particularly when their habitats were located near net pens.

Our findings emphasize the need for enhanced management strategies to mitigate the impact of salmon lice on wild fish, including stricter regulations on lice levels on farms, improved monitoring systems, and the development of innovative control measures. These measures are essential for safeguarding the health of both wild and farmed fish populations while minimizing the ecological risks of lice transmission.

INTRODUCTION

In recent years, the Atlantic salmon (*Salmon salar*) population in the North Atlantic has experienced a sharp decline due to numerous natural stressors, including pollution, ocean warming, and marine overexploitation (Dadswell et al., 2021). Similarly, reports on Artic charr (*Salvelinus alpinus*) have highlighted a concerning decline in the Icelandic populations, with these reductions linked to ocean warming and rising parasitic loads (Malmquist et al., 2009; Simmons et al., 2019). The rapid increase of the aquaculture industry in recent years has been associated with numerous stressors, including pollution, genetic hybridization and introgression, as well as the increase of parasitic infestations, with these factors often contributing significantly to salmonid mortality (Bouwmeester et al., 2020; Quero et al., 2020).

One of the main challenges that the Icelandic and international salmon farming industry is facing today are high sea lice infestations, impairing significant effects on animal welfare and the health of both farmed and wild salmonids (Cerbule et al., 2020; Torrissen et al., 2013). The precarious state of wild salmonid populations underscores the urgency of investigating sea lice infestations. Gathering data on sea lice infestations in populations of wild salmonids is a vital step toward understanding their health impacts and developing effective mitigation strategies to support the sustainability of salmonid populations in Iceland.

Despite its relatively small size, Iceland is the world's largest producer of Arctic charr and ranks as the sixth largest producer of Atlantic salmon, with total farmed salmonid production reaching 52,389 tons as of October 2024 (Matvælastofnun, 2024a). The aquaculture industry has grown into a vital part of Iceland's economy, making substantial contributions through job creation, export revenue, and regional development. Its impact is especially significant in the West- and Eastfjords, the primary regions for marine aquaculture in Iceland, where sea cages are located.

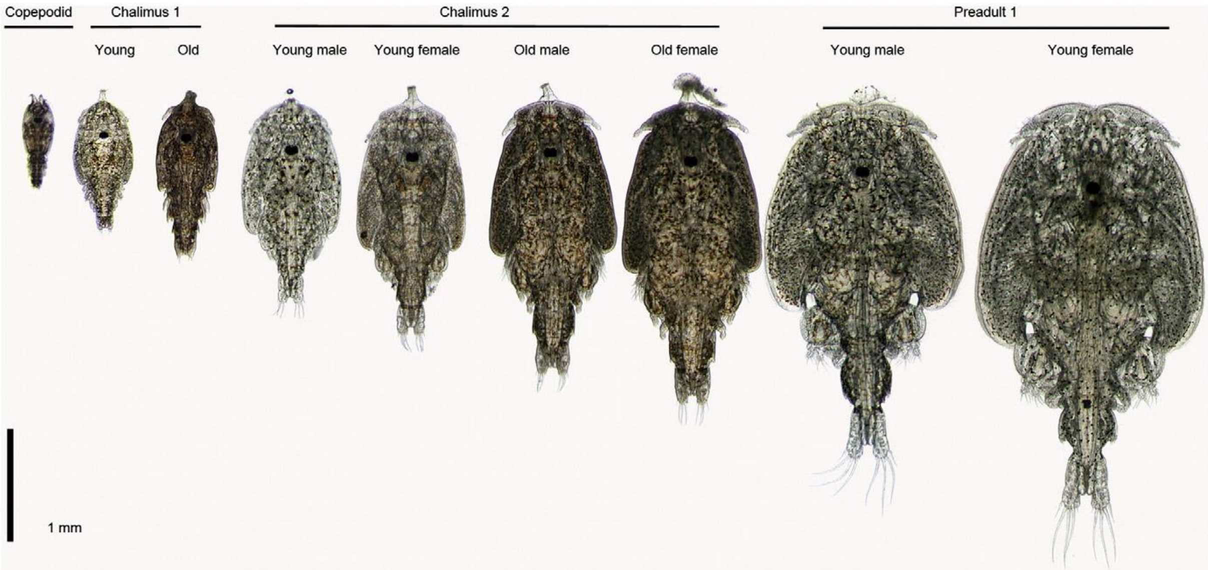
Around 85% of Iceland's aquaculture is marine based, with fish typically raised in open sea cages. This method allows for the open exchange of water, nutrients, and biological organisms between the sea cage environment and the surrounding ecosystem. Numerous studies have documented a range of potential environmental impacts from open-sea fish farming, including nutrient pollution (Arechavala-Lopez et al., 2022), habitat disruption (Bath et al., 2023), and the spread of diseases (Assefa et al., 2018), highlighting the critical need for environmental monitoring.

Although Iceland's economy heavily depends on marine resources, no large-scale, long-term environmental monitoring program is currently in place to assess aquaculture's effects on the natural marine environment. Legislation governing the fish farming industry originates in the 1970s to support a then-nascent sector, and despite the industry's substantial growth over the past decade, regulatory frameworks have not been sufficiently updated to manage its present-day scale effectively. The establishment of continuous monitoring and research is essential to ensure the sustainability of fish farming practices and to mitigate negative effects on the marine ecosystem.

Sea lice biology

Sea lice are parasitic copepods (crustaceans) that spend the majority of their lifetime attached to their fish hosts. Two sea lice species can potentially infest salmonids in Icelandic coastal waters: the fish lice (*Caligus elongatus*) and the salmon lice (*Lepeophtheirus salmonis*). The fish lice are parasitic to various fish species, whereas the salmon louse is host-specific and exclusively attaches to salmonid species. In Iceland, fish lice have always been a component in fish ecology, whereas the abundance of salmon lice tremendously increased after the establishment of the aquaculture industry in Iceland (Matvælustofnun, 2024b).

After hatching, the planktonic sea lice disperse into the water column, where they develop into the infective copepodite stage (Boxaspen, 2006). The copepodites attach to the host through the frontal filament and become non-motile (Byrne et al., 2018). The lice molt and develop though multiple juvenile life stages while being attached to the fish and feed on the mucus, scales and blood of the fish. The lice become mobile again when they reach the preadult or adult stage, allowing the lice to change their host. The dispersal of preadult and adult stages can be motivated by a high lice density or by the absence of the opposite sex on the current host (Connors et al., 2011). The life span of female salmon lice has been determined under laboratory conditions, with individual females living up to 210 days. Sea louse generation time depends on temperature, spanning between 6 weeks (at 9°C) and 8-9 weeks (at 6°C) (Samsing et al., 2016). Even though cold and dark winter conditions reduce the time of egg and larval development significantly, the reproductive cycle for salmon lice is ongoing year-round (Boxaspen & Næss, 2000).



*Picture 1. Pictures showing different developmental stages of the salmon lice (*Lepeoptheirus salmonis*) (Eichner et al., 2015).*

Sea lice on wild salmonids

There are three native species of salmonids found in the marine habitats around Iceland; the Atlantic salmon, brown trout (*Salmo trutta*) and Arctic charr. All species are, at least partly, anadromous, meaning that they migrate between rivers and the marine environment. Adult salmonids migrate to freshwater habitats in the fall for spawning, then return to marine environments by early summer, where they spend the summer months feeding. During this time, sea lice attach to and remain with their hosts until the salmonids migrate back to freshwater.

The survival of sea lice in freshwater depends on their life stage: early juveniles cannot survive more than an hour, while larger juveniles and preadults endure for several days (Wright et al., 2016). Adult lice, however, can remain on salmonids for at least eight days after entering freshwater. During the winter period in freshwater, salmonids naturally shed sea lice. At the same time, their absence from the marine environment eliminates potential hosts for lice, disrupting their lifecycle during this season. However, farmed fish in marine net pens remain in the water year-round, providing ideal hosts for salmon lice to thrive – despite low temperatures during the Icelandic winter (Matvælastofnun, 2024b). This ongoing availability of hosts enables the lice to sustain their life cycle and increases the risk of reinfection for nearby wild fish populations.

Impact on sea lice on fish health

Salmon lice are parasitic organisms that feed on the mucus, skin, and blood of fish, causing severe health issues for their hosts. Infected fish experience elevated cortisol levels, disruptions in osmoregulation, and a weakened immune system (Gallardi et al., 2019). The combination of an impaired immune response and the loss of the protective mucus layer leaves the fish highly vulnerable to viral infections and diseases (Barker et al., 2019). These effects are compounded by secondary impacts, including reduced growth, diminished swimming ability, and impaired reproduction, ultimately resulting in a significant increase in fish mortality and reduced fecundity (Bui et al., 2016; Grimnes & Jakobsen, 1996).

A salmon lice risk index, designed to quantify mortality risk and compromised fish health due to sea lice infestations, was proposed in Norway by Taranger et al. (2015), and is based on infestation levels described as number of salmon lice per gram of fish weight. Salmonid mortality is estimated to be 100% when salmonids (>150 g) are infected by 0.15 lice/g, and 0.3 lice/g for juvenile salmonids (<150 g) (Taranger et al. 2015). These estimates are based on international studies conducted both in the field and in the wild, highlighting the severe effects sea lice can have on salmonid growth, reproductive success and survival.

Industry and sea lice treatment

Elevated sea lice levels in fish cages necessitate treatments, which incur substantial costs for the aquaculture industry and contribute to adverse impacts on the surrounding marine ecosystem. Common sea lice treatments (pesticides) used in Iceland are Alpha Max©, Salmosan© and Slice©. While Slice© is applied as in-feed medication, Salmosan© and Alpha Max© are externally applied to the fish and pumped into the open net pens to bathe the fish. The chemical bathing of fish results in high financial costs for the aquaculture companies.

Moreover, high sea lice infestation levels on farmed fish have led to emergency slaughtering. For example, in 2023 all 2,936,917 Atlantic salmon from 12 net pens in Tálknafjörður had to be slaughtered and disposed of (Matvælastofnun, 2023). These tremendous losses of farmed fish were attributed to high sea lice infestations, likely resulting from poor prevention and late responses of the fish farming industry as well as authorities (Matvælastofnun, 2024b).

The financial impact of sea lice infestations arises from treatment expenses and production losses due to reduced growth and increased fish mortality. These costs have been estimated to range between €0.2/kg (Costello, 2009) and €0.44/kg (Abolofia & Wilen, 2017). Accounting for inflation (based on *cost of living index and consumer price index)*, the estimated cost for 2024 would be 74 ísk./kg. and 110 ísk./kg. respectively. Based on the life stock numbers of farmed fish in marine net pens in October 2024 (Matvælastofnun, 2024a), the estimated annual financial losses for the Icelandic fish farming industry due to sea lice infestations range between 2.9 and 4.8 billion Icelandic krona (calculations in supplementary).

These costs account only for the industry's monetary losses. Compromised health and mortality of wild salmonids associated with sea lice infestations in regions with intensive fish farming are not included in the financial calculations presented above. Sea lice induced mortality rates of wild salmonids have been estimated to be 18% of overall mortality (Vollset et al., 2016). In Norway, in areas with high sea lice load, the mortality of out-migrating salmon post-smolts has been determined to be > 30 %. Estimations from the Norwegian Scientific Advisory Committee for Atlantic Salmon suggest that salmon lice reduced the number of returning salmon in Norway by 118,000 wild salmon between 2012 and 2019 (VRL, 2020).

This study investigated sea lice infestation levels on wild salmonids in the Icelandic Westfjords during July and August 2024. The primary objectives were to (1) compare lice abundance across different areas, (2) examine the influence of temperature on lice abundance, and (3) explore the relationship between lice abundance on wild fish and farmed fish. Insights from this research can inform sea lice management strategies in the Icelandic aquaculture industry, contributing to the protection and conservation of wild salmonid populations.

METHODS

The study was conducted in the Westfjords of Iceland, where anadromous Atlantic salmon, Arctic charr and sea trout populations inhabit the fjords during summer months. Study sites were selected near rivers known to host salmonid populations, as well as in fjords with and without active fish farming operations (Figure 1). The fishing sites were named after the respective fjords: Veiðileysufjörður (VL) and Leirufjörður (LEI) in Jökulfirðir, Kaldalón (KAL) in Ísafjarðardjúp, Borgarfjörður (BF) and Trostansfjörður (TR) in Arnarfjörður, Tálknafjörður (TA), and Patreksfjörður (PA). Adverse weather conditions during the summer of 2024 disrupted the sampling schedule, prompting the decision to discontinue sampling in the East Fjords.

Picture 2. Fishing vessel next to a gill net placed in Arnarfjörður.

Field work

Sampling was conducted using gill nets (mesh size 21 mm and 24 mm) at each study site during July and August 2024. At each fishing site (Figure 1), six nets were placed into the ocean in proximity to the salmon rivers and close to vegetated, rocky shore habitats, known as suitable salmonid habitats. The nets were positioned perpendicular to the shoreline, spaced approximately 50 m to 100 m apart to ensure effective coverage and minimize overlap. Each gill net was 25 m long and 2 m deep, with upper floats and lower weights. Nets were kept in the water for a period of 6 h on each of three consecutive days each month, or until the desired number of fish was caught. The desired sampling number was 25 to 30 fish per month but was not always reached due to poor weather and poor catchability at times. During placement in the water, the nets were continuously monitored, and any fish caught were promptly removed to prevent entanglement, harm or loss of sea lice. Dead fish were individually placed into labelled bags and stored in a cooler to maintain preservation until they could be transported to the laboratory facilities.

Sea temperature, conductivity and dissolved oxygen were collected at each sampling day in proximity to the nets at water surface, 1 m and 2 m depth. The following devices were used to measure water parameters:

Temperature:	HQ40d (Hach), CastAway CTD (Son Tek)
pH:	HQ40d með PHC101 nema (Hach), CastAway CTD (Son Tek)
Conductivity:	HQ40d (Hach), CastAway CTD (Son Tek)
Dissolved oxygen:	HQ40d með LDO rannsaka (Hach)

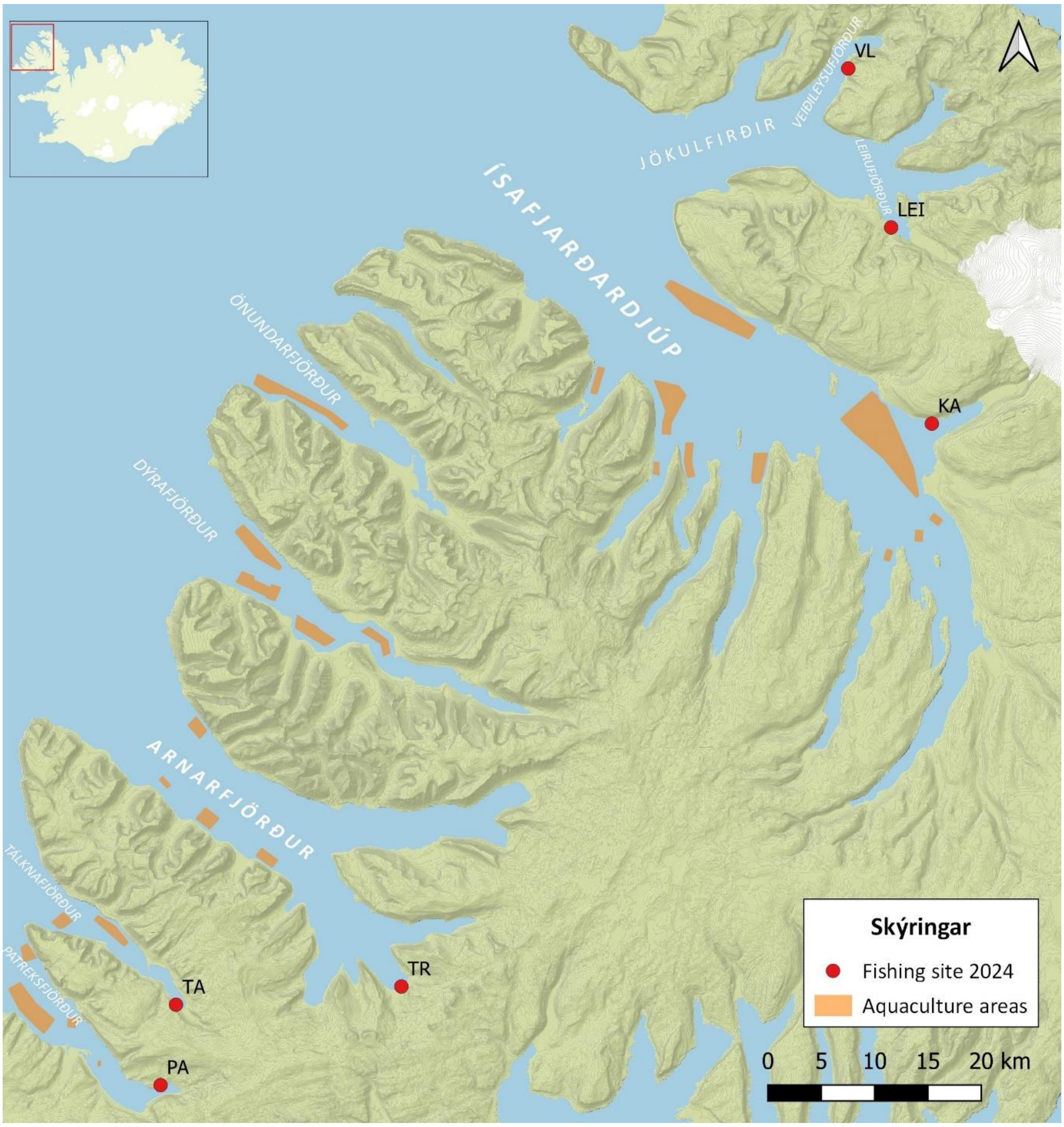


Figure 1. Fishing sites of the sea lice monitoring in July and August 2024. Aquaculture areas marked in red. (map: Hulda Birna Albertsdóttir)

Data processing and preparation

Data collected in the lab included fish species, body length and weight, as well as species (*Lepeophtheirus salmonis* or *Caligus elongatus*), sex and life stage of sea lice found attached to the fish. Specifically, for the lice, species and gender were assigned to adult and preadult stages, however not for mobile stages, including copepodites and chalimus. Catch rate was calculated for every site and month by dividing fish number by the number of nets and fishing hours. Lice counts from the caught salmonids were used to determine infestation rates, quantified as prevalence (the proportion of infested fish), abundance (the mean number of lice per fish, infected and uninfected) and intensity (mean number of lice per infested fish) for each site and date (Bush et al., 1997).

The risk levels, serving as indicators of the impact of sea lice on fish mortality, compromised growth, or reduced reproductive success, were calculated based on the Norwegian Risk Assessment for Sustainable Aquaculture framework (Taranger et al., 2015). Risk levels for salmon lice infestation are categorized based on the number of lice per gram of fish weight, with thresholds delineating "low," "moderate," and "high" risk levels (Taranger et al., 2015). A "high risk" level, associated with 100% mortality, is defined as infestation rates of ≥0.15 lice per gram for salmonids weighing over 150 g, and ≥0.3 lice per gram for juvenile salmonids weighing under 150 g. Conversely, a "low risk" level is indicated by infestation rates between 0.1 and 0.2 lice per gram for salmonids over 150 g, and below 0.01 lice per gram for juveniles under 150 g (see S_Table 1 for further details).

The proportion of female adult salmon lice on farmed salmonids for each sampling area was obtained from the ASC reports from Arnarlax (arnarlax.is) and Arctic Sea Farm (arcticfish.is) and from *Fishtalk* through Háafell. The mean value of maximum weekly lice proportions was calculated for each month and study fjord. The distance between fishing site and nearest net pen was calculated based on the shortest distance over water.

Data analysis

A generalized linear model (GLM) was generated to investigate the effect of temperature, lice abundance in fish farms and distance to fish farms on the lice abundance on wild salmonids. Explanatory variables included the *month* (July and August), fish *length* (TL), mean *water temperature* measured at fishing sites for each month, abundance of female adult *lice on farmed fish* and the *distance* between fishing site and nearest net pen. The model was fitted with an interaction effect between *lice on farmed fish* and *distance*. The response variable was the lice abundance on individual wild salmonids, including fish without lice. The statistical family was a negative binomial distribution with a log link function. The model was implemented using the *glm.nb* function from the MASS package in RStudio (Studio Team, 2020). Model diagnostics included the inspection of fitted residuals, residual deviation using a Kolmogorov-Smirnov (KS) test (p=0.2), and an outlier test (p=1) using the R package DHARMa (Hartig, 2022).

RESULTS

A total of 174 salmonids were caught in the Westfjords during July and August in 2024; of those 93 were Arctic charr, 80 sea trout and 1 Atlantic salmon. The species composition showed a clear difference in their latitudinal distribution; the majority of fish caught in Ísafjarðardjúp and Jökulfirðir were Arctic charr, while sea trout was the most common fish species caught in Arnarfjörður, Tálknafjörður and Patreksfjörður. The body length (TL) of Arctic charr was between 17.4 and 44.1 cm (mean= 27.2 cm), while sea trout were between 14.1 and 53.4 cm long (mean= 26.3 cm) (Figure 2). No fish were caught in Borgarfjörður (Arnarfjörður).

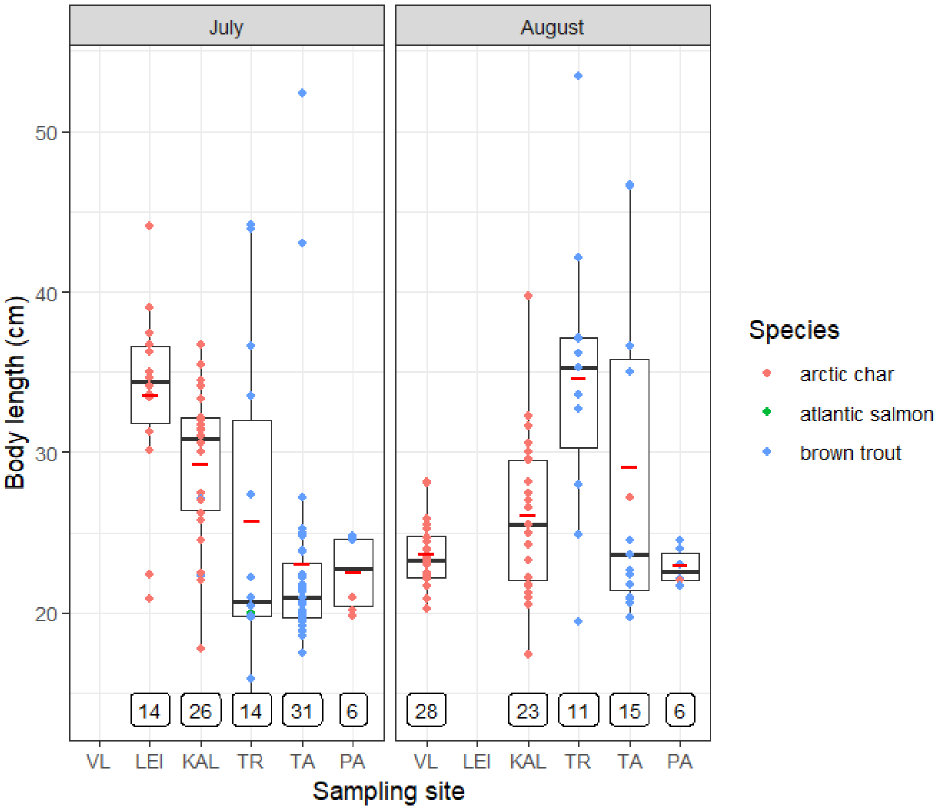


*Figure 2. Boxplot on fish body length plotted for each sampling site during July and August 2024. Catch numbers from each sampling site and month are stated below each boxplot. Points indicate individual fish length combined with species information (color). Each box represents 50% of the fish length distributed between the 1st and 3rd quartiles and whisker length is limited to 1.5*interquartile range.*

Fish Catches and Sea Lice Abundance

A total of 4722 lice were recorded on 174 fish, with approximately 70% of the captured fish carrying sea lice. Among the preadult and adult lice, 98% were identified as salmon lice (*Lepeophtheirus salmonis*), while only two were fish lice (*Caligus elongatus*). Sea lice numbers were notably higher in July (n = 3996) compared to August (n = 726) (Table 1). The highest infestation was observed on a sea trout from Trostansfjörður in Arnarfjörður in August, carrying 283 lice. Overall, sea trout exhibited significantly higher lice abundance, averaging 62.5 lice per fish, compared to Arctic charr, which averaged 8.7 lice per fish. Among sites, the highest amounts of sea lice were found on fish from Trostansfjörður (n=1619) and Tálknafjörður (n=2589) both during July and August, leading to high values in lice abundance and intensity for these fjords (Table 1). For all sites and sampling periods, prevalence ranged between 0.2 (LEI in July) and 1.0 (TR in August), abundance ranged between 1 (KAL in August) and 81.9 (TR in July), and intensity ranged between 2.2 (KAL in August) and 127.3 (TR in July) (Table 1).

Table 1. Summary on salmonid numbers, lice count, lice prevalence, abundance and intensity (mean ± standard deviation) for each study site and the months July and August. Prevalence: proportion of infested fish; abundance: mean number of lice per fish of all fish; intensity: mean number of lice per infested fish.

Fishing site	Fish number	Lice count	Prevalence	Abundance	Intensity
			JULY		
LEI	14	18	0.2	1.3 (±4.3)	6 (±8.7)
KAL	26	371	0.8	14.3 (±16.6)	16.9 (±16.8)
TR	14	1146	0.6	81.9 (±94.4)	127.3 (±89.2)
TA	31	2423	0.9	78.2 (±58.2)	86.5 (±54.9)
PA	6	38	0.8	6.3 (±6.3)	7.6 (±6.2)
			AUGUST		
VL	28	45	0.6	1.6 (±2.2)	2.8 (±2.2)
KAL	23	22	0.4	1 (±1.5)	2.2 (±1.5)
TR	11	473	1.0	43 (±81.1)	43 (±81.1)
TA	15	166	0.6	11.1 (±12.9)	18.4 (±11.8)
PA	7	20	0.9	2.9 (±2)	3.3 (±1.6)

The sampling times at each site and month were influenced by weather conditions and catch success. The target catch of 30 fish was exceeded only once in Tálknafjörður in July, where 31 fish were caught. The catch rate, defined as the number of fish per fishing hour and net, ranged from 0.09 (Patreksfjörður in July) to 0.65 (Veisuleysifjörður in August) (S_Table 2).

Life stages of sea lice

The sessile stages of salmon lice were predominantly observed in July, accounting for 88.6% of the total lice found. These stages consisted primarily of *chalimus* (94.3%), with only 5.7% identified as *copepodites* during both months. The proportion of preadult and adult life stages increased from July to August at all sites. Of the preadult and adult lice stages in August, 99% were salmon lice (SL) and of those, 40% were females and 60% were males. Only 2 fish lice (FL) were found on the salmonids, with both being female preadults (KAL and TA). Fish from Tálknafjörður had both highest number of sessile lice (n=2316) and preadult lice (n=105) in July as well as highest numbers of preadult (n=82) and adult lice (n= 21) in August. The highest numbers of sessile stages (n=420) in August were found on fish from Trostansfjörður (Figure 3, S_Table 3).

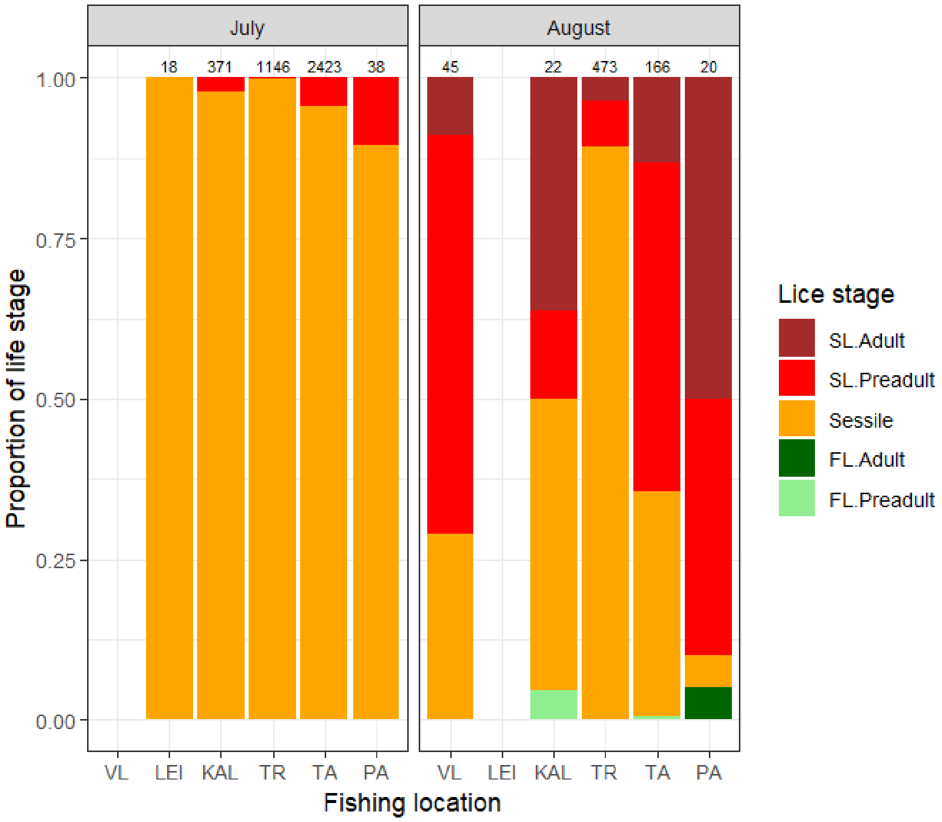


Figure 3. Proportion of life stages of salmon lice (SL) and fish lice (FL) for each site and the months July and August. The numbers displayed at the top of each column represent the total count of lice recorded at each site and for each month.

Highest temperatures measured in Tálknafjörður, Patreksfjörður and Kaldalón in July were 12.4°C, 11.8°C, and 11.1 °C, respectively. The temperatures measured in Leirufjörður and Trostansfjörður in July were 9.2°C and 8.6°C, respectively. In August, highest temperatures were measured in the southern Westfjords (TA, TR and PA) and ranged between 10.6°C and 11.0°C, while temperatures in Ísafjarðardjúp (with KAL) and Jökulfirðir (with VL) were relatively cool, with 8.8°C and 8.7,°C, respectively (S_Table 4, details in S_Table 5).

Risk assessment

In July, high and moderate risk levels were observed in over 60% of the fish caught at several locations. Specifically, in Kaldalón, 35% of the fish were at high risk and 27% at moderate risk. In Trostansfjörður, 64.3% of fish were classified as high risk, and in Tálknafjörður, 87.1% of the fish were at high risk, with 3.2% at moderate risk. In contrast, Leirufjörður (7.7%, high) and Patreksfjörður (16.7%, moderate) had lower proportions of moderate or high-risk levels, with only a small number of fish affected in July. In August, the proportions of fish in high and moderate risk levels ranged from 20% to 45.5%. Of the fish caught in Trostansfjörður, 45.5% of fish were at high risk and 36.4% at moderate risk. In Tálknafjörður, 23.5% of salmonids were at high risk and 17.7% at moderate risk in August. In Kaldalón, 20.8% of the fish in Kaldalón were at moderate risk. Additionally, all fish in Veisuleysifjörður and Patreksfjörður in August were assigned a low risk level, indicating minimal lice infestation in these areas during that period (Figure 4).

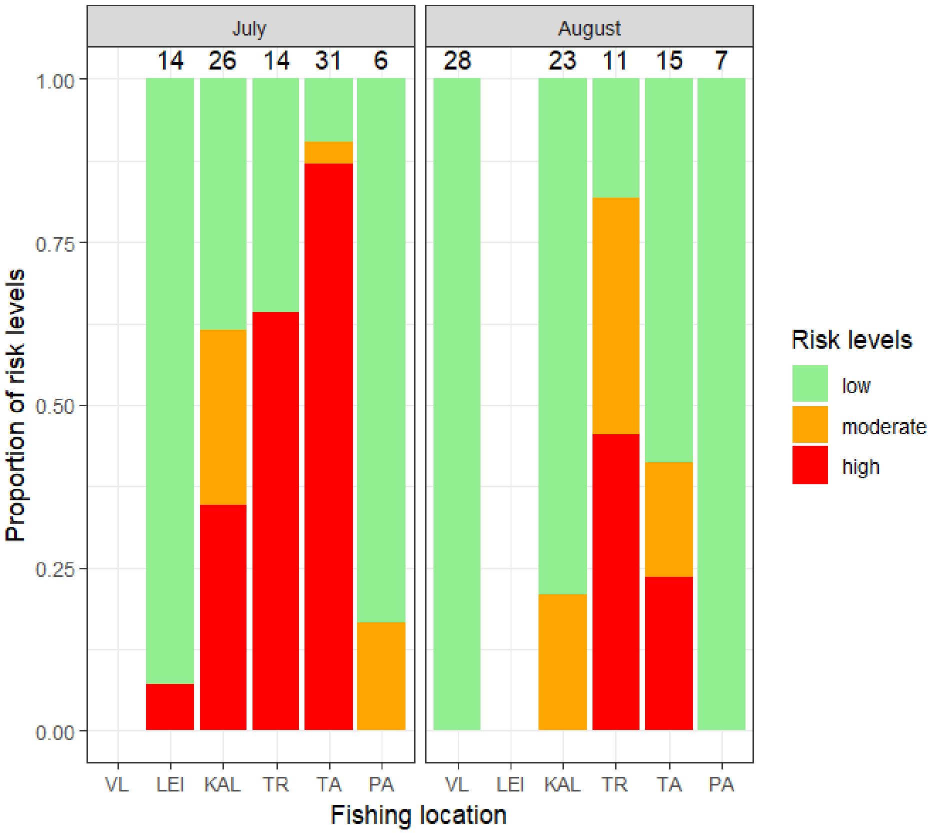


Figure 4. Proportion of risk levels calculated for each fishing site and month based on the Norwegian risk assessment for sustainable aquaculture (Taranger et al., 2015). The numbers displayed at the top of each column represent the number of fish caught at each site and month and include both fish heavier and lighter than 150 g.

Data analysis

The GLM results indicated a significant increase in lice abundance on wild salmonids with higher infestation levels in fish farms ($p < 0.001$). This effect intensified with proximity to the farms ($p < 0.001$). Lice abundance also increased significantly with temperature ($p < 0.001$) and between July and August ($p = 0.04$). Additionally, smaller fish exhibited higher lice loads compared to larger fish ($p = 0.01$). Model diagnostics indicated no significant residual deviations from the assumed distribution (KS-test, $p = 0.2$), no extreme outliers ($p = 1$), and no significant overdispersion (S_Table 6)

DISCUSSION

Ocean temperature

The study outcome indicated considerable variation in sea lice abundance both between months and among sampling sites. Model results suggested water temperature as a major driver for sea lice abundance on wild salmonids, with higher temperature leading to increased infestation levels on the wild fish. This aligns with established understanding, as temperature plays a critical role in determining the development and growth rates of salmon lice (Sandvik et al., 2021). The developmental time significantly decreases with increasing water temperatures within the thermal range from 6°C to 21°C (Are Hamre et al., 2019), ultimately leading to greater infection success of salmon lice at higher temperatures (Dalvin et al., 2020).

The Norwegian MRI reported a 3-fold increase in salmon lice numbers in Northern Norway in September 2024, which has been linked to unusually high-water temperatures measured in previously cool waters in the North of Norway (Hoddevik, 2024).

In Icelandic aquacultures, salmon lice infestation levels vary significantly between the two primary aquaculture regions: the Westfjords and the Eastfjords (Matvælustofnun, 2024b). Elevated salmon lice levels have been reported in the Westfjords following the expansion of the aquaculture industry, while fish farms in the Eastfjords have reported minimal infestations (Matvælustofnun, 2024b). This disparity in lice levels may be influenced by differences in sea temperature regimes. Between 2015 and 2024, the mean sea temperature in the Eastfjords (Stöðvarfjörður) during August was 7.5°C (±0.9°C), compared to 10°C (±1.0°C) in the Westfjords (Æðey) (source: https://sjora.hafro.is).

Results from this study have further shown that the temperature gradient within the Westfjords, from north to south, appears to impact sea lice abundance across different fjords. Higher lice infestation levels have been observed in Arnarfjörður and Tálknafjörður compared to Jökulfirðir and Ísafjarðardjúp. Climate projections indicate a clear trend of rising sea temperatures, particularly in Arctic and Subarctic regions. This warming is expected to favour the abundance and distribution of salmon lice, potentially exacerbating lice infestations in Iceland’s aquaculture systems in the near future (Sandvik et al., 2021).

Salmon lice on farmed fish

Sampling was conducted in areas with both high and low fish farm density. Our findings revealed a strong correlation between lice loads on wild fish and the abundance of adult female salmon lice in the fish farms. Wild salmonids in areas with high lice abundance in fish farms exhibited significantly higher lice infestations. This effect was further amplified when the distance between salmonid habitats (fishing sites) and the nearest net pen was small.

Salmon lice in their copepodite stage, often described as the infectious life stage, are passively dispersed through ocean currents and serve as the primary vector for transferring lice between farmed and wild fish (Boxaspen, 2006). In Scotland, studies have shown that higher densities of copepodite stages occur in waters surrounding sea cages when Atlantic salmon density in the net pens is high, increasing the risk of lice infection for wild fish (Penston & Davies, 2009). In Iceland (Matvælastofnun, 2023) as well as other countries the expansion of fish farming has led to significant increases in salmon lice abundance, both within and beyond the cage environment (Dempster et al., 2021).

Between 2000 and 2007, as aquaculture in Iceland was developing, fish lice were frequently reported on farmed fish, although salmon lice were noted “only in exceptional cases” (Matvælastofnun, 2007). By 2010, salmon lice were occasionally observed (Matvælastofnun, 2010). After 2015, as fish farming expanded, lice numbers surged, prompting the first emergency lice treatment (chemical bathing) in 2017. Since then, chemical treatments have risen exponentially (Matvælastofnun, 2024b), closely correlating with the increasing scale and density of aquaculture, clearly linking sea lice prevalence to farming intensity in Iceland.

Several laboratory studies demonstrated the negative impact of salmon lice on salmonid development, reproduction and survival (Finstad *et al.*, 2012, Tveiten *et al.*, 2010, Bjørn & Finstad, 1997). Those studies, among others, were guidelines for the Norwegian risk assessment of the aquaculture industry (Taranger et al., 2015) which outlines risk categories for lice infested wild fish. The current study identifies several sites in Iceland where wild salmonid populations face a high risk of health issues and mortality due to lice infestations according these Norwegian Risk Assessment guidelines. Our findings indicate that in certain areas, particularly those with both high aquaculture activity and elevated temperatures, the risk extends beyond individual fish to threaten entire salmonid populations.

Fishing method

Higher sea lice numbers were observed in July compared to August, with a greater proportion of mobile stages (preadult and adult lice) found on wild fish in August. While sessile stages remain strongly attached to the fish, mobile stages can actively adhere to the fish's skin, enabling them to move across its surface (Bui et al., 2024). However, the use of gill nets to capture fish can dislodge these mobile stages, leading to an underestimation of lice counts on infected fish. Notably, many fish exhibited irregular marks on their skin, consistent with salmon lice bite marks, but had few or no lice present. This suggests that mobile stages may have detached during the capture process, potentially leading to an underestimation of their presence in this study.

To address this issue, we recommend adopting alternative fishing methods that keep the fish alive during capture. Fish traps have proven to be an effective and sustainable method for monitoring sea lice on salmonids (Taranger et al., 2015). This approach allows researchers to anesthetize the fish for the lice count and then release the fish back into the wild. Implementing fish traps in future sea lice monitoring efforts will help ensure more accurate counts of mobile lice stages, reduce the loss of lice during handling, and, importantly, minimize the ecological impact of monitoring on wild salmonid populations in Iceland.

Secondary effects and alternative lice treatments

While the negative effects of sea lice are often associated with farmed and wild fish, secondary impacts, including harmful effects from lice treatment drugs on the surrounding ecosystem, must also be considered. Pesticides used for sea lice treatments are typically applied by pumping them into open net pens, allowing the chemicals to disperse freely into surrounding waters. These pesticides are not specific to salmon lice and can pose significant risks to non-target crustacean species.

The toxicity of Alpha Max has been tested on several crustacean species, including the American lobster (*Homarus americanus*), sand shrimp (*Crangon septemspinosa*), and mysids (*Praunus flexuosus*) (Burridge et al., 2014). Exposure to Alpha Max and Salmosan, even in diluted concentrations (Alpha Max: 2,000-fold; Salmosan: 30-fold), was lethal to these species. Additionally, the effects of these chemicals are neither site-specific nor short-lived. They can spread across large areas and persist in sediments for extended periods. For example, chitin synthesis-inhibiting chemicals used in sea lice treatments were detected in sediments up to 1,400 meters from Norwegian aquaculture sites and remained present 8–22 months after the last treatment (Parsons et al., 2021).

Compounding the issue, the efficiency of chemical treatments diminishes as salmon lice develop resistance to these pesticides (Aen et al., 2015). This growing resistance reduces the effectiveness of treatments, necessitating alternative approaches to managing sea lice in aquaculture (Coates et al., 2021). Thus, Icelandic aquaculture companies have begun to introduce alternative strategies to reduce sea lice loads in sea cages, though these efforts remain limited in scale. Implemented methods include, for example, sea lice curtains, lumpfish as biological controls, freshwater bathing, thermal treatments, and lice lasers. While these strategies show promise, their widespread adaptation has yet to be achieved.

Alternative treatments to delousing chemicals that pose minimal harm to the marine ecosystem have been developed and proven effective, such as thermal, mechanical and freshwater treatments (Aldrin et al., 2023). Future efforts should focus on advancing, applying, and installing treatments capable of sustainably maintaining low sea lice levels in fish farms. The timing and effectiveness of these treatments could be significantly improved through a better understanding of sea lice distribution in coastal waters. In countries like Norway, Ireland, and the Faroe Islands, sea lice distribution models have become essential tools for managing outbreaks and implementing preventative measures. For instance, Norway's hydrodynamic lice distribution model (Bøhn et al., 2022) incorporates data on water temperature, the number of adult female lice per fish (reported weekly by fish farms), the estimated number of fish in farms (reported monthly), and the rate of nauplii release into surrounding waters. These inputs are fed into a dispersion model that predicts the movement and distribution of salmon lice larvae, based on oceanographic conditions such as currents, temperature, and salinity. Results of these models inform decision making, with areas showing high risk being closed temporarily until infestation risk has been reduced below a certain threshold.

Developing a similar model for Iceland would be a critical step in managing sea lice more effectively. Such a model could help maintain low infestation levels, reduce the impact of sea lice on the environment and aquaculture, and address the increasing challenges posed by rising sea lice levels due to climate change and increasing aquaculture activity.

Conclusion and recommendation

The growing challenges posed by sea lice infestations underscore the urgent need for stricter regulations and robust enforcement in Iceland's aquaculture industry. This study on wild salmonids in the Icelandic Westfjords revealed significant variation in lice abundance across months and regions, emphasizing the critical influence of environmental factors such as water temperature. A strong correlation between lice levels on wild and farmed fish further highlights the importance of comprehensive management plans targeting both aquaculture operations and surrounding ecosystems.

To protect wild salmonid populations and support sustainable aquaculture, a forward-thinking approach is necessary. This includes integrating advanced monitoring systems and predictive models to better understand lice distribution patterns. Developing and implementing alternative, eco-friendly treatments will be key to addressing the dual challenges of rising lice levels and environmental conservation in the face of climate change.

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SUPPLEMENTARY

Calculations of estimates on financial losses for the Icelandic fish farming industry due to sea lice infestations for 2024.

Costs associated with sea lice treatment and impact on farmed fish based on literature:

0.2€/kg (Costello, 2009) =29.02 ISK/kg (conversion rate in November 2024)

0.46$/kg (Abolofia & Wilen, 2017) = 63.3 ISK/kg (conversion rate in November 2024)

Accounting for inflation (*cost of living index and consumer price index*) → https://www.statice.is/inflation-calculator/

29.02 ISK (Jan 2009) → 55 ISK (Oct 2024)

63.3 ISK (Jan 2017) → 92 ISK (Oct 2024)

Life stock in Icelandic marine net pens, see table below: 52,389,000kg (Oct 2024, see below)

55ISK/kg*52,389,000kg= 2,881,395,000 ISK

92ISK/kg*52,389,000kg= 4,819,788,000 ISK

https://www.mast.is/is/maelabord-fiskeldis (05.12.2024):

Lok tímabils	Lífmassi	Fóður	Afföll	Slátrað	Förgun
July 2023	33,725	6,691	245	2,435	0.0
August 2023	37,256	8,684	426	3,791	0.0
September 2023	41,012	9,472	145	4,220	0.2
October 2023	38,611	7,541	1,589	6,951	317.8
November 2023	36,824	5,957	996	6,297	168.0
December 2023	37,109	5,153	355	3,918	19.1
January 2024	34,690	3,535	322	5,026	22.9
February 2024	31,938	2,359	439	4,238	35.8
March 2024	31,169	2,359	359	2,397	37.7
April 2024	31,430	2,410	338	1,648	43.7
May 2024	33,661	3,330	199	734	22.6
June 2024	36,834	4,932	255	1,584	28.4
July 2024	43,786	8,196	127	659	7.9
August 2024	48,594	10,403	141	4,119	10.3
September 2024	51,644	10,114	229	6,080	9.6
October 2024	52,389	9,886	197	7,578	13.5

S_Table 1. Criteria for the mortality risk levels from parasite loads on wild fish assigned for different size classes and are based on number of lice per gram of fish weight following Taranger et al. (2015).

fish weight	mortality % (or compromised reproductivity)	lice per gram
<150g	100	> 0.3
<150g	50	0.2 -0.3

<150g	20	0.1 -0.2
>150g	100	>0.15
>150g	75	0.1-0.15
>150g	50	0.05-0.1
>150g	20	0.01-0.05
>150g	0	<0.01

S_Table 2. Summary of number of gill nets, placement time of the nets in the water (fishing hours) and number of caught fish for each fishing for each site and month. Catch rate was calculated for every site and month by dividing fish number by the number of nets and fishing hours.

Fishing site	Month	Gill nets	Fishing hours	Fish number	Catch rate
KAL	July	6	13.7	26	0.32
LEI	July	6	10.0	14	0.23
BF	July	5	5.4	--	--
PA	July	6	11.5	6	0.09
TA	July	6	11.0	31	0.47
TR	July	6	11.6	14	0.20
KAL	August	6	11.0	23	0.35
BF	August	6	10.0	--	--
PA	August	5	5.0	7	0.28
TA	August	6	5.0	15	0.50
TR	August	6	11.0	11	0.17
VL	August	6	7.2	28	0.65

S_Table 3. Number of sea lice species and life stage for each site and month. SL=Salmon lice, FL= Fish lice, PA (in "species and life stage")=preadult, A=adult.

Month	Fishing site	Lice species and life stage	Lice counts
July	LEI	Copepodite	3
July	LEI	Chalimus	15
July	KAL	Copepodite	8
July	KAL	Chalimus	355
July	KAL	SL.PA.male	2
July	KAL	SL.PA.female	6

Month	Fishing site	Lice species and life stage	Lice counts
July	TR	Copepodite	214
July	TR	Chalimus	931
July	TR	SL.PA.female	1
July	TA	Copepodite	14
July	TA	Chalimus	2302
July	TA	SL.PA.male	45
July	TA	SL.PA.female	60
July	PA	Chalimus	34
July	PA	SL.PA.male	3
July	PA	SL.PA.female	1
August	VL	Copepodite	1
August	VL	Chalimus	12
August	VL	SL.PA.male	8
August	VL	SL.PA.female	20
August	VL	SL.A.male	1
August	VL	SL.A.female	3
August	KAL	Copepodite	2
August	KAL	Chalimus	8
August	KAL	SL.PA.male	2
August	KAL	SL.PA.female	1
August	KAL	SL.A.male	2
August	KAL	SL.A.female	6
August	KAL	FL.PA.female	1
August	TR	Copepodite	3
August	TR	Chalimus	417
August	TR	SL.PA.male	15
August	TR	SL.PA.female	19
August	TR	SL.A.male	9
August	TR	SL.A.female	8
August	TA	Copepodite	3
August	TA	Chalimus	53

Month	Fishing site	Lice species and life stage	Lice counts
August	TA	SL.PA.male	35
August	TA	SL.PA.female	47
August	TA	SL.A.male	5
August	TA	SL.A.female	16
August	TA	FL.PA.female	1
August	PA	Chalimus	1
August	PA	SL.PA.male	3
August	PA	SL.PA.female	5
August	PA	SL.A.male	3
August	PA	SL.A.female	7
August	PA	FL.A.female	1

Table 4. Mean values of water temperature and salinity measured at each fishing site and month at three different depths (surface, 1 m and 2 m).

Fishing	Temperature	Salinity
JULY		
KAL	11.1	30.8
LEI	9.2	35.0
BF	7.4	50.3
PA	11.8	44.5
TA	12.4	37.5
TR	8.6	50.7
AUGUST		
KAL	8.8	47.6
BF	7.7	50.8
PA	10.6	51.5
TA	10.7	49.8
TR	11.0	48.0
VL	8.7	53.1

S_Table 5: Detailed overview of water temperature, salinity, pH, dissolved oxygen and measurement depth for each site and month.

Month	Fishing Site	Depth (m)	Temperature (°C)	Salinity (xx)	pH	Oxygen (xx)
July	KAL	0	12.9	7.8	--	--
July	KAL	1	10.6	37.5	--	--
July	KAL	2	9.7	47.1	--	--
July	LEI	0	9	14.4	--	--
July	LEI	1	9.2	44.7	--	--
July	LEI	2	9.3	45.8	--	--
July	BF	0	7.5	50.3	8.2	13.3
July	BF	1	7.3	50.2	--	--
July	BF	2	7.4	50.5	--	--
July	PA	0	12.6	41.8	8.2	12
July	PA	1	11.5	45.1	--	--
July	PA	2	11.3	46.6	--	--
July	TA	0	12.8	21.9	8.8	12
July	TA	1	12.2	44.4	--	--
July	TA	2	12.1	46.3	--	--
July	TR	0	8.7	49.5	8.3	13
July	TR	1	8.6	51.2	8.3	12.7
July	TR	2	8.6	51.5	--	--
August	KAL	0	9	43.5	8.7	11.7
August	KAL	1	8.6	49	--	--
August	KAL	2	8.7	50.3	--	--
August	BF	0	7.9	50.2	8.2	11.8
August	BF	1	7.8	50.6	--	--
August	BF	2	7.3	51.6	--	--
August	PA	0	10.6	51.4	8.6	--
August	PA	1	10.6	51.5	--	--
August	PA	2	10.6	51.5	--	--
August	TA	0	*NA*	48.5	8.4	12.2
August	TA	1	10.7	50.4	--	--
August	TA	2	10.7	50.6	--	--
August	TR	0	11.1	42	--	11.8
August	TR	1	11	50.8	--	--
August	TR	2	11	51.2	--	--
August	VL	0	8.7	53.2	--	--

Month	Fishing Site	Depth (m)	Temperature (°C)	Salinity (xx)	pH	Oxygen (xx)
August	VL	1	8.7	53	--	--
August	VL	2	8.7	53.1	--	--

S_Table 6. Parameter estimates for the generalized linear model (GLM) summarizing the effect of covariates on the sea lice abundance on wild salmonids caught in the Westfjords 2024. The covariates included sampling month, body length, temperature, lice on farmed fish, and distance between fishing site and nearest net pen.

Parametric coefficient	Estimate	Standard error	z-value	p-value
intercept	-11.17	2.11	-5.29	1.20e-07
month	0.69	0.33	2.05	0.04
length	-0.04	0.02	-2.54	0.01
temperature	1.34	0.18	7.51	5.72e-14
lice on farmed fish	56.75	10.91	5.20	1.99e-07
distance	0.40e-2	0.02	0.27	0.79
*Lice on farmed fish*distance*	-7.76	1.63	-4.77	1.82e-06